Project X Performance by Stage

Project X Reference Design

Project X is the centerpiece of the Fermilab strategy to develop a world-leading Intensity Frontier program and lay the groundwork for eventual construction of a Neutrino Factory or Muon Collider. Project X is an integral part of the 2011 Fermilab Strategic Plan (A Plan for Discovery, https://www.fnal.gov/directorate/plan_for_discovery/).

The primary mission elements to be supported by Project X include:

1. Long-baseline neutrino experiments: Provide in excess of 2 MW of proton beam power onto a neutrino production target at any energy between 60 – 120 GeV.
2. Rare processes experiments: Provide MW-class, multi-GeV, proton beams supporting multiple precision experiments with kaons, muons, and neutrinos simultaneous with the long-baseline neutrino program.
3. Muon facilities: Provide a path toward a muon source for a possible future Neutrino Factory and/or a Muon Collider.
4. Nuclei and nuclear energy: Provide opportunities for implementing a program of Standard Model test with nuclei, ultra-cold neutrons, and nuclear energy applications.

A concept for a high intensity proton facility, designated the Project X Reference Design, has been developed that meets the high level design criteria listed above in an innovative and flexible manner. The Reference Design is shown schematically in Figure 1. The primary elements are:

- An H- source consisting of an ion source, 2.1 MeV RFQ, and Medium Energy Beam Transport (MEBT) augmented with a wideband chopper capable of accepting or rejecting bunches in arbitrary patterns at up to 162.5 MHz;
- A 3 GeV superconducting linac operating in continuous wave (CW) mode, and capable of accelerating an average (averaged over >1 μsec) beam current of 1mA, and a peak beam current (averaged over <1 μsec) of 5 mA;
- A 3 to 8 GeV pulsed superconducting linac capable of accelerating a peak current of 1 mA with a 5% duty cycle;
- A pulsed dipole that can split the 3 GeV beam between the neutrino and rare processes programs;
- An rf beam splitter that can deliver the 3 GeV beam to multiple (at least three) experimental areas;
- Modification to the Recycler and Main Injector Ring required to support delivery of 2 MW of beam power from the Main Injector at any energy between 60-120 GeV;
- All interconnecting beam transport lines.

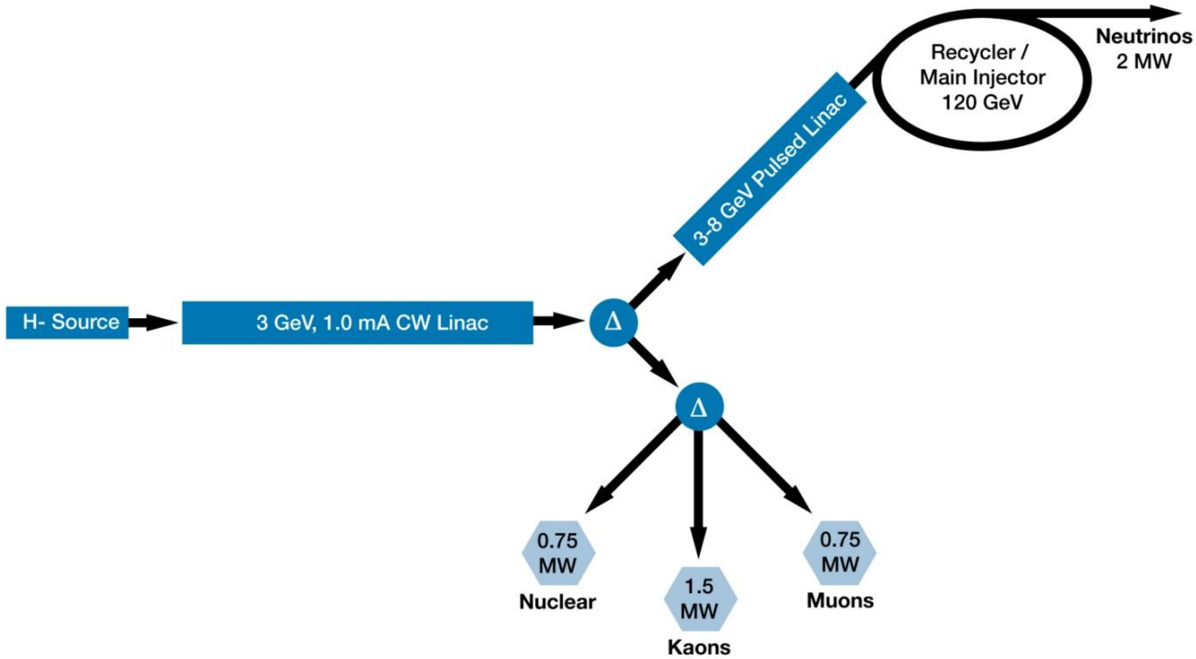


Figure 1: Schematic layout of the Project X Reference Design

The Reference Design provides a facility that will be unique in the world with unmatched capabilities for the delivery of very high beam power with flexible beam formats to multiple users. The Reference Design provides the framework for the R&D program for Project X currently underway.

Staging

Financial and budgetary constraints have led to available funding have led to consideration of a staged approach to Project X. Development of a staging plan for Project X is based on application of the following principles:

- Each stage should have a cost significantly below $1B.
- Each stage should present compelling physics opportunities.
- Each stage should utilize existing elements of the Fermilab complex to the extent possible.

- At the completion of the final stage the full vision of a world leading intensity frontier program at Fermilab should be realized.

A three stage approach to the Reference Design consistent with the above principles has been developed and is described below.

Stage 1

Stage 1 of Project X is comprised of a newly constructed 1 GeV, CW, superconducting linac operating with an average current of 1 mA. A small fraction (~2%) of the beam will be injected into the existing Booster. Injection at 1 GeV is projected to result in a 50% increase in the per pulse proton intensity delivered from the Booster to the Main Injector complex, relative to current operations. Stage 1 thus establishes the potential for delivering up to 1200 kW onto a long baseline neutrino target (either NuMI or LBNE). Depending upon the operating energy of the Main Injector and the allocation of the Main Injector timeline between neutrino production and a possible rare kaon experiment, significant power could also be devoted a program based on 8 GeV protons. The balance of available linac beam can be delivered to the Muon Campus currently under development, providing a factor of ten increase in beam power available to the Mu2e experiment, and/or to a newly developed experimental programs devoted to nuclear electric dipole moments (edm), ultra-cold neutrons, and possibly nuclear energy applications.

An additional substantial benefit of Stage 1 is that the existing 400 MeV linac will be retired from service, removing a substantial operational risk within the Fermilab proton complex.

Stage 2

Stage 2 is based on extension of the CW linac to 3 GeV, still with an average current of 1 mA. Stage 2 provides 3 MW of beam power at 3 GeV, with the capability of delivering flexible beam formats to multiple experiments. It is anticipated that a Main Injector based kaon experiment would be relocated to the 3 GeV linac in Stage 2. Also accommodated are any number of muon and nuclei based experiments. Injection into the Booster at 1 GeV will be retained, as will the available beam power at 1 GeV.

To support the Stage 2 performance the initial 1 GeV of the linac will be upgraded to 2 mA capability, with 1 mA available at 1 GeV and 1 mA transmitted into the 1-3 GeV linac section. In addition the Booster will be upgraded to 20 Hz capability.

Stage 3

Stage 3 completes the Reference Design via construction of a pulsed linac for acceleration of beam from 3 GeV to 8 Gev. This beam is delivered to the Recycler/Main Injector complex in support of the long baseline neutrino program. At Stage 3 >2MW of beam power is available at any energy between 60-120 GeV. Upgrades to the Recycler/Main Injector are required to support the increased beam power. Enhanced capability for delivery of 8 GeV beam, directly from the pulsed linac, is also created at this Stage. Beam capabilities at 1 and 3 GeV remain as in Stage 2.

In addition, with the completion of Stage 3 the existing 8 GeV Booster can be retired from service, taking the second substantial operating risk in the current program along with it.

Stage 4

Stage 4 is an upgrade to the Reference Design based on an increase in the current and duty factor of the pulsed linac. Stage 4 is primarily aimed at providing a 4 MW capability at 8 GeV, as required for a Neutrino Factory or Muon Collider. However, the beam power produced could be utilized in support of an 8 GeV neutrino program. Stage 4 has the secondary impact of also providing sufficient beam to the Recycler/Main Injector complex to support 4 MW operations at 6-120 GeV, contingent upon appropriate upgrades to those accelerators and the LBNE target station. ***Note that Stage 4 requires very significant R&D outside the scope of the current Project X program.***

PXIE

PXIE (Project X Injector Experiment) is a program of systems tests of the Project X front end that will be mounted before the end of the current decade. PXIE comprises the first 30 MeV of Project X and is being developed to Project X specifications. The basic capability is 1 mA at 30 MeV (30 kW) with the potential for upgrading to 2-5 mA.

Explanation of Tables

The tables below summarize the performance at all available beam energies at each stage. The organization of the tables is as follows:

- Each table describes beam performance in support of a particular program by Stage: Long Baseline Neutrino Program (Main Injector Fast Spill); 8 GeV Program (Booster in Stages 1 and 2, pulsed linac in Stage 3); 3 GeV Program; 1 GeV Program.
- Under each Stage there are two entries, corresponding to operations of the Main Injector at 120 GeV or at 60 GeV.

- There is a trade-off (proton economics) between beam power available for the Long Baseline Neutrino and 8 GeV program. The tables present a self-consistent set, based on the maximum beam power achievable in the Long Baseline Program and the corresponding minimum in the 8 GeV program. Subsequent to the tables is a set of figures displaying the trade-offs between the two programs.
- The beam formats for the 3 GeV and 1 GeV programs are flexible, subject to certain constraints that are described at the end of this document.

Stage 4 and PXIE parameters are described separately following the primary set of tables.

Long Baseline Neutrino Program

(Main Injector Fast Spill)	Stage 1		Stage 2		Stage 3		
	120	60	120	60	120	60	GeV
Maximum Beam Power*	1200	900	1200	1200	2450	2450	kW
Protons per pulse	7.5×10^{13}	7.5×10^{13}	7.5×10^{13}	7.5×10^{13}	1.5×10^{14}	1.5×10^{14}	
Pulse length	9.5	9.5	9.5	9.5	9.5	9.5	μsec
Number of bunches	504	504	504	504	504	504	
Bunch spacing	18.9	18.9	18.9	18.9	18.9	18.9	nsec
Bunch length (FWHM)	2	2	2	2	2	2	nsec
Pulse repetition period	1.2	0.8	1.2	0.6	1.2	0.6	sec

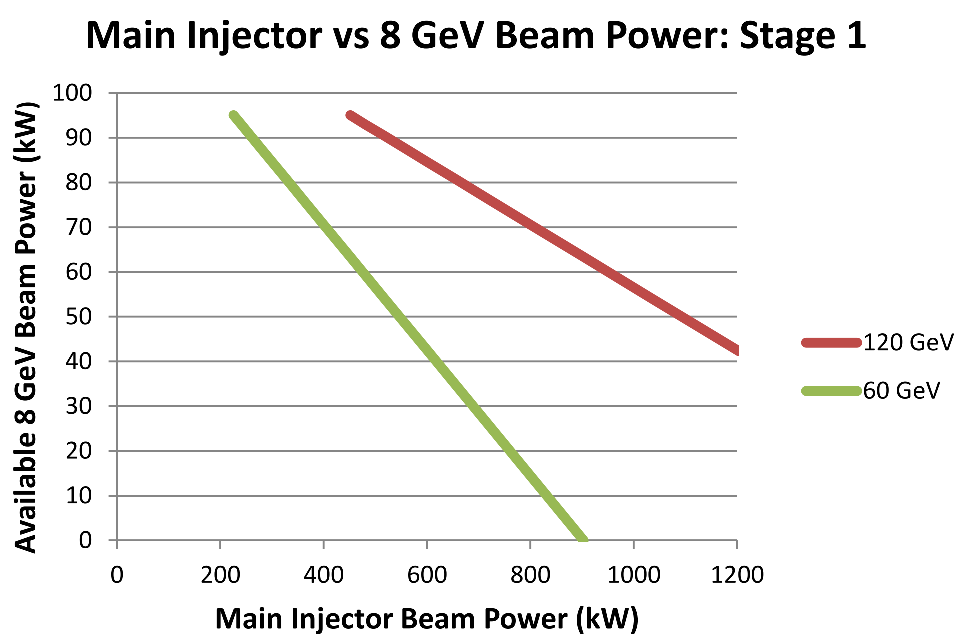
8 GeV Program	Stage 1 (Booster)		Stage 2 (Booster)		Stage 3 (Pulsed Linac)		
	120	60	120	60	120	60	GeV
Minimum Beam Power*	42	0	84	0	172	0	kW
Protons per pulse	6.6×10^{12}	6.6×10^{12}	6.6×10^{12}	6.6×10^{12}	2.7×10^{13}	2.7×10^{13}	
Pulse length	1.6	1.6	1.6	1.6	4300	4300	μsec
Number of bunches	81	81	81	81	140,000	140,000	
Bunch spacing	18.9	18.9	18.9	18.9	30	30	nsec
Bunch length (FWHM)	2	2	2	2	.04	.04	nsec
Pulse repetition rate	15	15	20	20	10	10	Hz

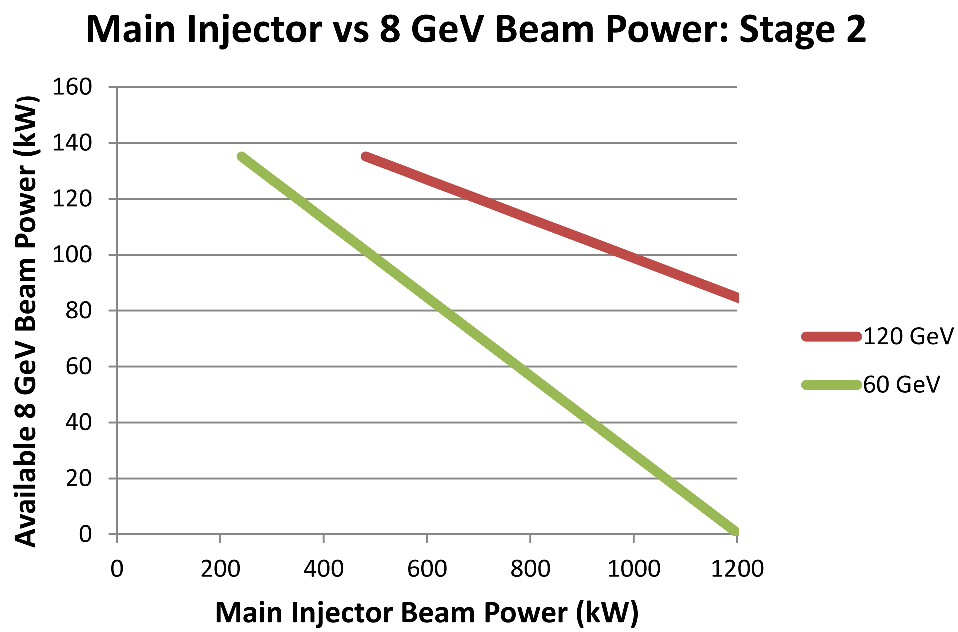
3 GeV Program	Stage 1		Stage 2		Stage 3		
	120	**60**	**120**	**60**	**120**	**60**	**GeV**
Beam Power	NA	NA	3000	3000	2870	2870	kW
Protons per second	NA	NA	6.2×10^{15}	6.2×10^{15}	6.2×10^{15}	6.2×10^{15}	
Pulse length	NA	NA	CW	CW	CW	CW	μsec
Bunch spacing**	NA	NA	Programmable		Programmable		nsec
Bunch length (FWHM)	NA	NA	.04	.04	.04	.04	nsec

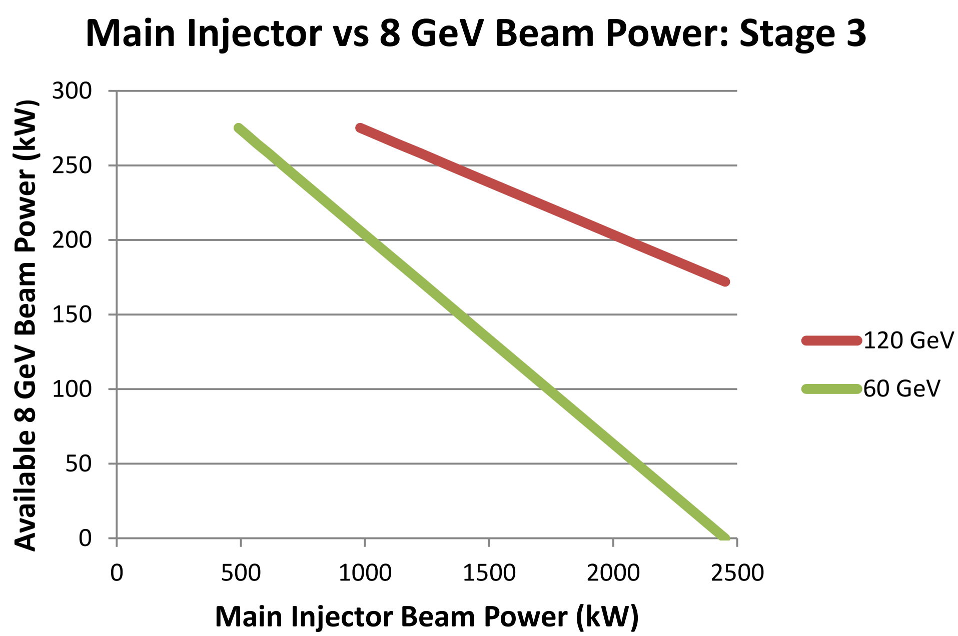
1 GeV Program	Stage 1		Stage 2		Stage 3		
	120	**60**	**120**	**60**	**120**	**60**	**GeV**
Beam Power	984	984	980	980	1000	1000	kW
Protons per second	NA	NA	6.2×10^{15}	6.2×10^{15}	6.2×10^{15}	6.2×10^{15}	
Pulse length	NA	NA	CW	CW	CW	CW	μsec
Bunch spacing**	NA	NA	Programmable		Programmable		nsec
Bunch length (FWHM)	NA	NA	.04	.04	.04	.04	nsec

Notes

* Beam Power available from the Main Injector and at 8 GeV are dependent upon the disposition of protons provided at 8 GeV and the operational energy of the Main Injector. It is assumed that the disposition of protons will be a program planning decision based on the physics opportunities at the time. Below are presented the dependence upon available beam power at 8 GeV as a function of beam power available from the Main Injector, at each stage and for each of two operating energies.



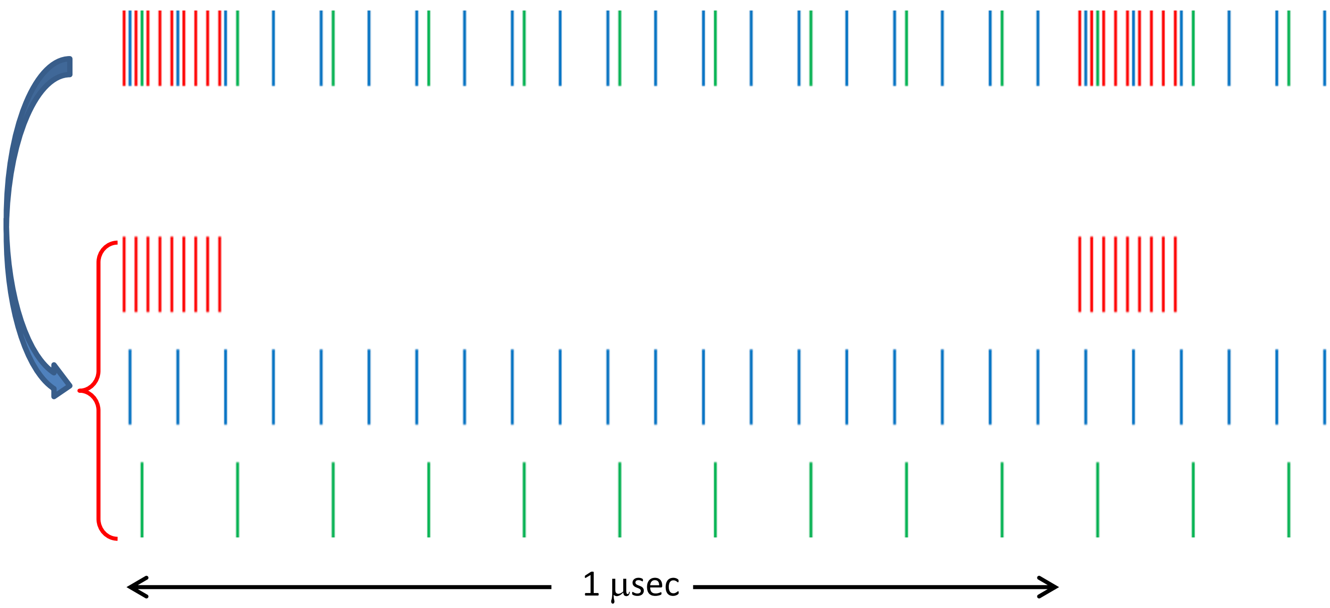

Main Injector vs 8 GeV Beam Power: Stage 2
Available 8 GeV Beam Power (kW)
160
140
120
100
80
60
40
20
0
0
200
400
600
800
1000
1200
Main Injector Beam Power (kW)
120 GeV
60 GeV


Main Injector vs 8 GeV Beam Power: Stage 3
Available 8 GeV Beam Power (kW)
300
250
200
150
100
50
0
0
500
1000
1500
2000
2500
Main Injector Beam Power (kW)
120 GeV
60 GeV

** Independent bunch structures can be provided from the 1 and 3 GeV linac to three experimental areas simultaneously. The bunch pattern in any particular area must conform to the following requirements:

- Each bunch contains up to 1.9×10^8 particles (H- ions);
- Bunches in each experimental area must be separated by either 12.4, 24.8, 49.6, or 99.2 nsec (80, 40, 20, 10 MHz);
- The bunch patterns must repeat every 1.0 μsec;
- The total current, summed over the three experimental areas, must be 1 mA averaged over the 1.0 μsec period.

An example is given below. The upper drawing shows bunches in the 3 GeV linac, color coded in terms of their ultimate experimental destination. The bottom three drawings show the deconvolution into the structures seen in the three experimental areas. The red area has a 1 MHz macrostructure and a 80 MHz microstructure; the blue area has a 20 MHz beam structure; the green area a 10 MHz beam structure. The number of particles/bunch is 1.7×10^8 and beam power to the three areas is 700, 1540, and 770 kW respectively.



PXIE

PXIE Program

	PXIE Program	Upgrade	
Beam Energy	30	30	MeV
Beam Current	1	5	mA
Beam Power	30	150	kW
Pulse length	CW	CW	
Bunch spacing**	Programmable	Programmable	
Bunch length (FWHM)	1	1	nsec

**Bunch spacing has the same capabilities as the Project X Reference Design

Stage 4

Long Baseline Neutrino Program
(Main Injector Fast Spill)

	Stage 4		
	120	**60**	**GeV**
Maximum Beam Power	4100	4100	kW
Protons per pulse	2.6×10^{14}	2.6×10^{14}	
Pulse length	9.5	9.5	μsec
Number of bunches	504	504	
Bunch spacing	18.9	18.9	nsec
Bunch length (FWHM)	2	2	nsec
Pulse repetition period	1.2	0.6	sec

8 GeV Program

	Stage 4		
	120	**60**	**GeV**
Minimum Beam Power	3700	3400	kW
Protons per pulse	2.1×10^{14}	2.1×10^{14}	
Pulse length	6700	6700	μsec
Number of bunches	220,000	220,000	
Bunch spacing	30	30	nsec
Bunch length (FWHM)	.04	.04	nsec
Pulse repetition rate	10	10	Hz

3 GeV Program

	Stage 4		
	120	**60**	**GeV**
Beam Power	2700	2700	kW
Protons per second	6.2×10^{15}	6.2×10^{15}	
Pulse length	CW	CW	
Bunch spacing**	Programmable		
Bunch length (FWHM)	.04	.04	nsec

1 GeV Program	**Stage 4**		
	120	**60**	**GeV**
Beam Power	1000	1000	kW
Protons per second	6.2×10^{15}	6.2×10^{15}	
Pulse length	CW	CW	
Bunch spacing**	Programmable		
Bunch length (FWHM)	.04	.04	nsec